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Research note

Analysis of welding conditions based on induced thermal irreversibilities in welded structures: Cases of welding sequences and preheating treatment

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Abstract Preheating treatment and employing a proper welding sequence are introduced as two efficient approaches for reducing residual stresses in welding processes. Selecting a right welding sequence and a proper preheating temperature for a weld system are crucial tasks, since welding residual stresses are inevitably produced in a welded structure. However, obtaining residual stresses is very complex, and much time is needed in some cases, particularly for the modeling and prediction of residual stresses in welded structures. So in this work, we attempt to show that these stresses depend on generated entropy during the arc welding process. Thus by obtaining thermal irreversibility effects from temperature distribution, due to a variation of different welding parameters, selection of optimum factors to achieve minimum residual stress is not only possible, but easier to undertake. In the proposed method, it is not a necessity to obtain residual stress values, and one can predict the behavior of residual stress qualitatively. To do so, 3D numerical models are employed to study the similar behavior of created residual stresses and entropy due to a variation of different preheating temperatures and three common welding sequences.

1. Introduction

Arc welding is one of the most important material-joining processes widely used in industry. Among the merits of such welded structures are high joint efficiency, water and air tightness and low fabrication cost. Due to localized heating by the welding process and subsequent rapid cooling, residual stresses and distortion can occur near butt–welded joints. High residual stresses in regions near the weld may promote brittle fracture, fatigue or stress corrosion cracking. Therefore, various methods are suggested for reducing residual stresses and the control of distortion in weldments. But among these, here in this work, the preheating and selection of a proper welding sequence are introduced as two efficient techniques for these purposes. Preheating involves raising the temperature of the parts to be welded before welding. Hence, preheating prevents development of cold cracks by decreasing the cooling rate of welds and heat affected zones. It also increases the toughness of welds, especially at low temperatures, and restrains shrinkage stress [1,2]. Many researchers have tried to estimate the effect of preheating temperatures on residual stress behavior. Teng and Lin [3] discussed the changes in residual stress magnitude, due to different preheating temperatures, in steel plates. Also Kadivar et al. [4] employed a 2D numerical model for investigating preheating temperatures on cooling time, the temperature field and residual stresses. Majdnia [5] showed that preheating and postheating treatment play significant roles in reduction of residual stress. Moienian [6] described preheating treatments and their advantages in different metals. He also presented the proper temperatures and situation for these metals. On the other hand, employment of a proper welding sequence can show itself as an effective and simple approach to decrease residual stress. The advantage of this method is that it does not require special equipment, as do most heat treatments; it can also be used in different situations [7]. Accordingly, developing the correct welding sequence and predicting welding residual stresses for welding systems are essential for achieving a safe design.

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For example, Kihara, as reported by Masubuchi [8], emphasized that selection of a suitable welding sequence can reduce residual stresses and distortion in weldments.

Kadivar et al. [9], while modeling their welding processes using 2D cases, obtained residual stresses for three common welding sequences, and compared the results with each other. Teng et al. [10] appraised the various sequence effects in multi-pass welding and circular paths. Nami et al. [11] studied two common welding sequences in a rectangular plate.

Traditionally, for control of welding parameters, such as preheating and welding sequences, to obtain a good welded joint with minimal detrimental residual stress, a manufacturer required time-consuming trial and error methods for their development [12,13].

On the other hand, analytical methods for prediction of stress distribution are accurate, but limited to simple geometries with several assumptions. For these reasons, numerical modeling seems to be a valuable option [14].

Despite various advantages of numerical methods, they are very complex, and much time is spent, in some cases, particularly for the modeling and prediction of residual stresses in welded structures. Furthermore, because of the many assumptions made in modeling stresses, some results are far from experimental data.

In this article, we employ generated entropy during welding processes to predict residual stress behavior due to the variation of different preheating temperatures and welding sequences, qualitatively. By this powerful tool, it is not required to get busy with complicated modeling of residual stresses, and one can estimate probable existent residual stress behavior in weldments before beginning welding under real conditions.

2. Entropy generation

Entropy generation is associated with thermodynamic irreversibility, which is present in all actual heat transfer processes and results in a loss of available work. The contemporary trend in the field of heat transfer and thermal design is to apply the second law of thermodynamics and its design-related concept of entropy generation minimization [15,16]. The entropy generation minimization concept and its usage as an optimization technique was investigated extensively by Bejan [17–19]. He emphasizes that heat transfer processes and devices are inherently irreversible (steady producer of entropy).

Heat transfer plays a principal role in welding processes, so due to different heat transfer mechanisms, various thermal fields are formed in weldments. A thermal field, among many factors that produce residual stresses and distortions, is the most significant origin of thermal loads and residual stresses [20,21].

Therefore, by studying the amount of entropy generated, these thermal fields can be taken into consideration for predicting residual stresses, qualitatively. In the conventional method for obtaining the best parameters, initially the temperature field is solved independently from the mechanical solution and then used as an input for mechanical analysis. After that, from obtained residual stress values, the best and optimum parameters can be selected. Figure 1 presents this analysis procedure [10]. However, in the proposed method, the second part of the analysis (mechanical analysis), which is very complex and time-consuming, has been eliminated, and one can easily find the best parameters by studying the amount of entropy generated. In other words, variations of different welding parameters affect temperature distribution directly and/or indirectly.

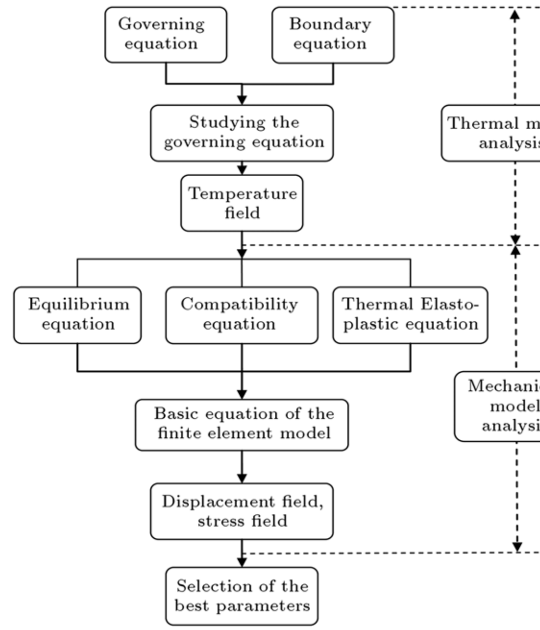


Figure 1: Flow diagram of the selection of the best parameters by obtaining the residual stresses and using mechanical model analysis [10].

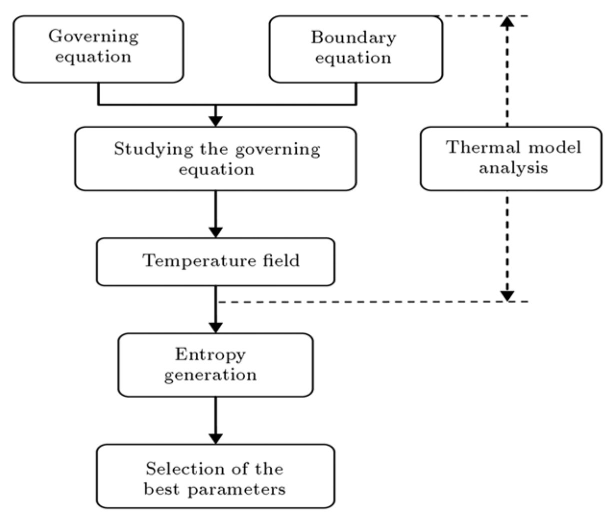


Figure 2: Proposed flow diagram of how to select the best parameters.

Therefore, in view of the fact that the thermal field is the most significant factor to produce entropy and residual stresses, through various temperature distributions, various magnitudes of generated entropy and residual stress are obtained. Hence the similarity of the behavior of entropy generation and residual stress under the influence of different parameters is set as a basis in the proposed method. Thus, without trying to obtain residual stresses directly, the behavior of residual stresses, due to variations of different parameters, can be predicted qualitatively. The following sections will show this procedure for two important parameters; preheating and welding sequences.

Flow diagram of the suggested procedure is shown in Figure 2.

3. Theoretical consideration

The 2nd law statement for a point size control volume is [19]:

$$s'''_{gen} = \rho \frac{Ds}{Dt} + \nabla . \left(\frac{q}{T}\right) \geq 0, \tag{1}$$

where q represents the heat flux and s is specific entropy per unit volume. The total entropy generation rate, $\dot{S}_{gen}$, is expressed in WK^{-1} and defined as:

$$\dot{S}_{gen} = \int_V s'''_{gen} \mathrm{d}V. \tag{2}$$

For the heat transfer phenomenon, the heat flux may be assumed as:

$$q = -k\nabla T. \tag{3}$$

But the governing equation of heat conduction (which is valid for welding processes [1–4,6]) with constant thermal conductivity is:

$$\rho c \frac{\partial T}{\partial t} - k\nabla^2 T = 0. \tag{4}$$

An alternative statement of the 2nd-law of thermodynamics for this case is [22]:

$$s'''_{gen} = \frac{k}{T^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right]. \tag{5}$$

In other words, if one introduces entropy flux $\phi(x, y, z, t)$ as:

$$\phi = \frac{q}{T} = -k\frac{\nabla T}{T}, \tag{6}$$

then, total entropy generation rate per unit volume, quantifying the extent of induced irreversibilities as a result of heat transfer, can be expressed as [23]:

$$\lambda = \frac{1}{T^2}(q).(\nabla T) = k\frac{1}{T^2}(\nabla T).(\nabla T) = \frac{\phi^2}{k}. \tag{7}$$

As a matter of fact, if temperature distribution in a domain is available, obtaining total entropy generation due to heat conduction during the welding process is trivial.

4. Model analysis

Numerical methods have several useful advantages that should not be overlooked. Thus we employ finite element methods to simulate the welding process under different conditions. Initially, the welded region of a 500 mm × 500 mm × 5 mm aluminum plate is considered for three-dimensional modeling [24]. Cubic 3-D elements with 8 nodes on their corners are used for meshing the weld region (see Figure 3). The plate material is Aluminum 1100, which has several usages in aviation industries. To determine temperature history profiles, a nonlinear transient thermal analysis is employed. The history dependent (transient) heat transfer problem involves an incremental scheme with several small time increments. The solution at a given time increment is obtained by using the solution at a previous time increment as an initial condition [25]. It is worth mentioning that the molten puddle motion (speed of welding) is modeled using a birth and death technique [11,20]. Also, convection and radiation heat transfer are taken into consideration in this model (details in [26,27]).

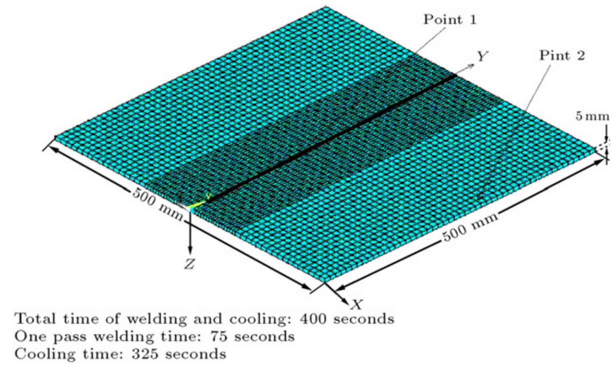


Figure 3: Detail and finite element mesh of welded region (Aluminum plate).

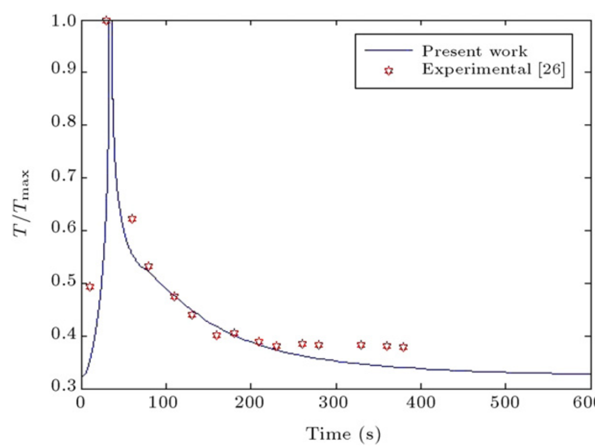


Figure 4: Calculated and measured values of temperature profile during single-pass arc welding for point 1. Point 1 is located in the vicinity of the weld line (Figure 3).

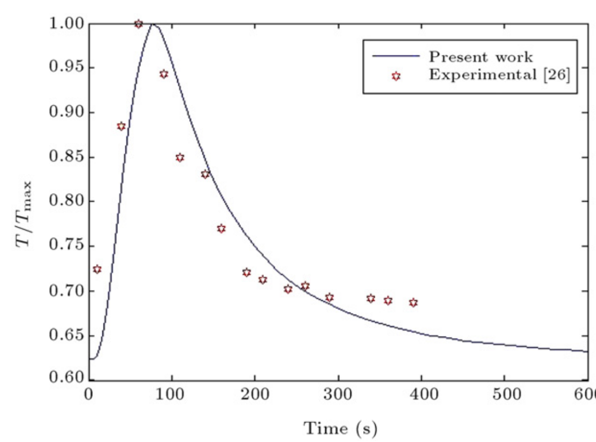


Figure 5: The calculated and measured values of temperature profile during single-pass arc welding for point 2. Point 2 is located 24 cm apart from the weld line (Figure 3).

For two points (the first is adjacent to the weld line and the other is far from it, as illustrated in Figure 3), the temperature profiles are shown in Figures 4 and 5. The presented computed results and the experimental data of Asle Zaeem [25] are also plotted in the same figures (T_{max} in these figures refers to the

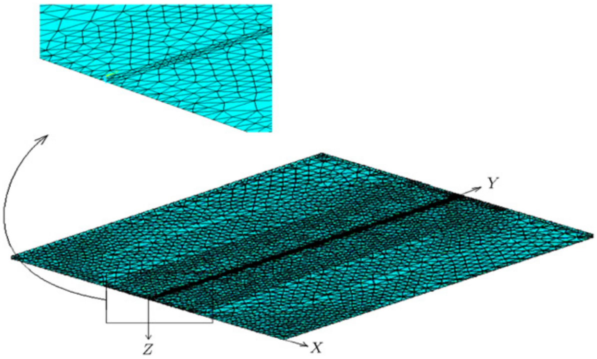


Figure 6: Finite element mesh of welded region: case of 16396 pyramid elements (Aluminum plate).

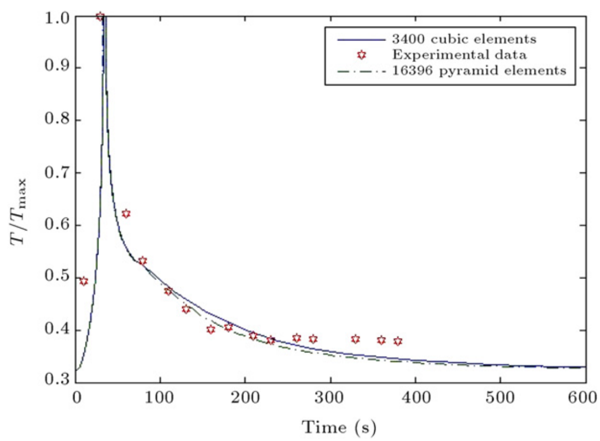


Figure 7: Temperature distribution at point 1 for two cases: (1) 3400 cubic elements and (2) 16,396 pyramid elements.

maximum temperature of the above mentioned points during the welding process).

It is clear that the differences between numerical and experimental results are very small and temperature profiles have a similar behavior. Thus, the comparison verified that the results of the present model would be comparable to the experimental one and so the model is satisfactory.

Then the elements that used for meshing the weld region are changed from 3400 cubic elements to 16396 pyramid ones (Figure 6). The results for the temperature distribution of point 1 are illustrated in Figure 7. This Figure shows that the temperature distribution is independent of the type and number of elements.

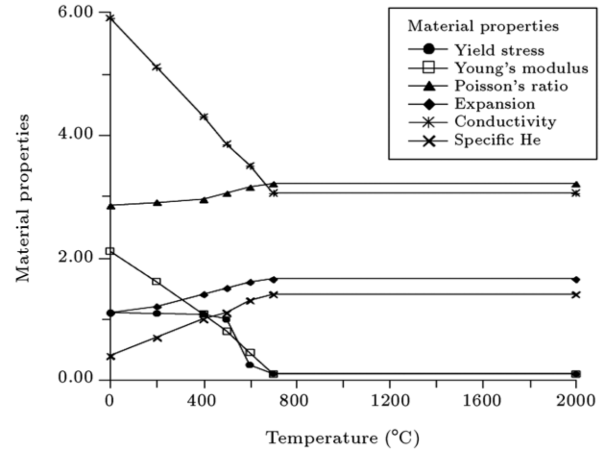
In the next step, the proposed methodology is applied to the numerical modeling for a 300 mm × 200 mm × 5 mm steel plate that is used in various references [3,10]. The plate material is SAE 1020, and its thermal and mechanical properties are dependent on the temperature history, as illustrated in Figure 8.

Figure 9 depicts the dimensions and finite element mesh of this welded plate. More than 2400 3D elements are used in this model. The arc welding simulation is completely similar to the aluminum plate case.

5. Preheating treatment

The preheating treatment is considered an important technique for reducing residual stress and undesired distortion in welding processes. In this section, the effect of this technique on residual stress and entropy will be investigated. The temperature distribution of similar points for three cases (without preheating, preheating at 200 °C, and preheating at 400 °C) is shown in Figure 10. This figure indicates that the peaks of temperature profiles have higher values at higher preheating temperatures. (In this figure, points *A* to *E* are located from the weld line to the margin of the weld plate.)

When temperature distribution is calculated from thermal analysis, entropy generation rate ($\dot{S}_{gen}$) is obtained based upon Eq. (2). Results are displayed in Figure 11 for three preheated cases. The total entropy generation in the whole welded plate can be obtained by integrating $\dot{S}_{gen}$ with respect to time. In other words, if the area under the curve (Figure 11) is calculated, the total entropy generation for each individual case can be obtained. The Compound Simpson Integration Method is employed for this procedure and results are reported in Table 1. As can be seen, the total entropy generation decreases with an increase in preheating temperature. Similarly, Figure 12 illustrates [3] that by applying higher preheating temperatures, the residual stresses decrease.



Symbol	Material properties	Unit
●--σ_y	Yield stress	$\times 10^8$ Pa
□---E	Young's modulus	$\times 10^{11}$ Pa
▲---υ	Poisson's ratio	$\times 10^{-1}$
◆---α	Expansion	$\times 10^{-5}$ m/m-K
✳---k	Conductivity	$\times 10^2$ W/K, m
✕---c	Specific heat	$\times 10^2$ J/K, kg

Figure 8: Thermal and mechanical properties of weldment (Steel plate (SAE 1020)) [3,10].

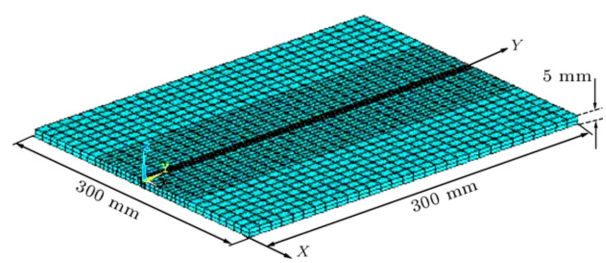


Figure 9: Dimensions and finite element mesh of welded region (Steel plate).

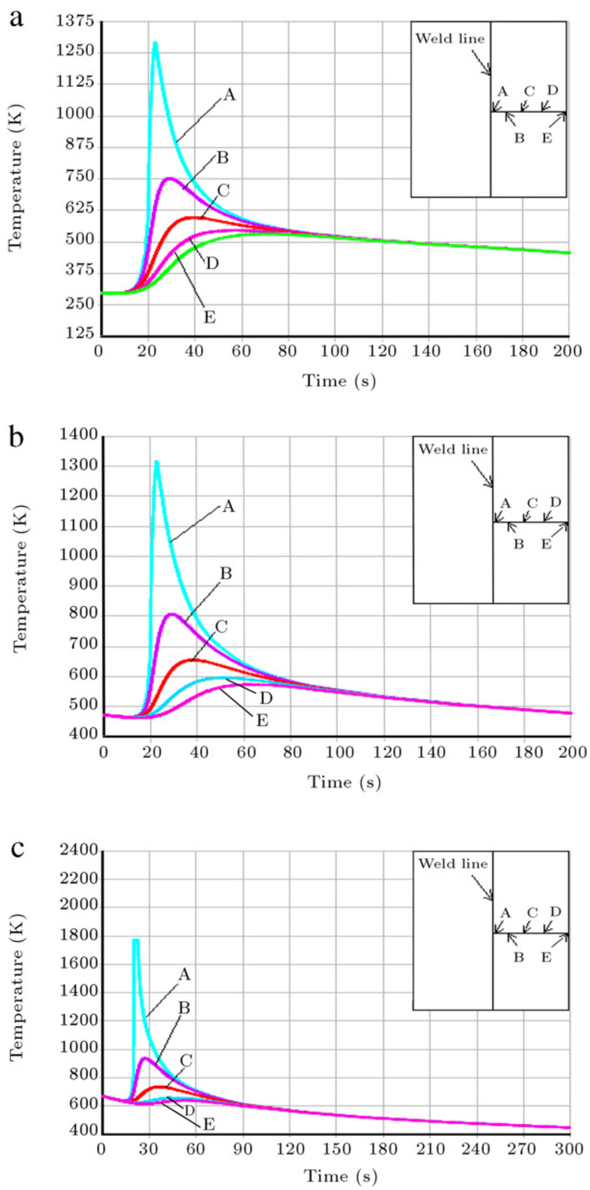


Figure 10: Temperature distribution of similar points (A, B, C, D, E) [A (adjacent to weld line) to E (far from weld line)] for three cases: (a) without preheating; (b) preheating with 200 °C; and (c) preheating with 400 °C.

Table 1: Variation of total entropy generation with different preheating temperatures.

Preheating temperatures (°C)	Total entropy generation (J/°K)
None	74.2
200	49.05
400	30.76

According to the coordinate system of Figure 9, the presented results illustrated in Figure 12 are related to the points with [50 Y 0] coordinates.

The decrease of generated entropy could be the result of a reduction in thermal gradient in the welded plate, due to preheating treatment. At the same time, the positive effect of preheating on the cooling rate causes a decrease in residual stress values. Therefore, these results, in connection with resid-

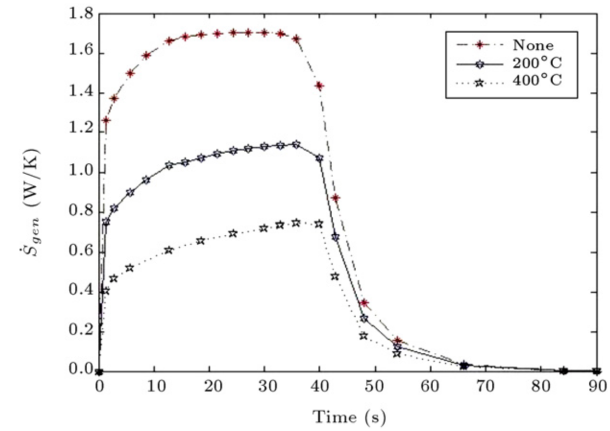


Figure 11: The effect of preheating treatment on entropy generation rate (Steel plate).

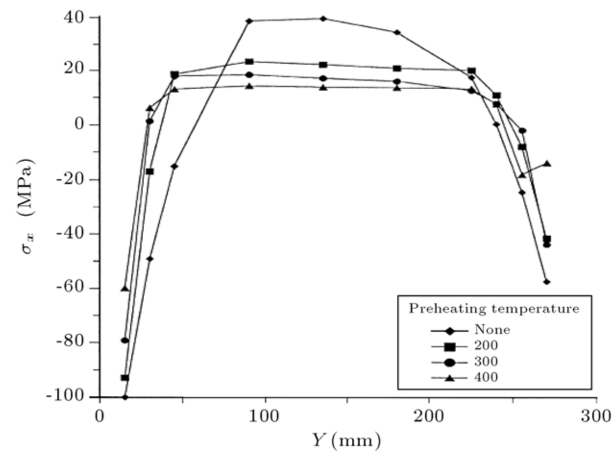


Figure 12: The effect of preheating treatment on transverse residual stresses (Steel plate) [3].

ual stresses, are in line with our findings concerning entropy generation (Table 1).

Afterwards, we attempt to model and obtain residual stresses directly in an aluminum plate. Anand's elastic–viscoplastic model is used for mechanical analysis [1,11]. The obtained results are comparable with results of total entropy generation changes, due to variations in preheating temperatures (Figures 13 and 14). As these figures reveal, when the aluminum plate is preheated to 225 °C, lower magnitudes of residual stress and entropy are generated.

We found that time spent throughout the proposed method is one fifth that of a conventional approach (obtaining residual stresses directly). Moreover, the proposed method's complexity is considerably less than the conventional one. Finally, from the above results, one can find that the behavior of entropy generation and residual stress distribution, with respect to different preheating temperatures, is very similar. In other words, when residual stress goes up, the total entropy generation shows the same behavior and vice versa.

6. Welding sequences

In order to reduce residual stress and distortion in long butt-welded or path-welded joints, various types of welding sequence can be used. The selection of a proper welding sequence with minimal residual stress is an important practical

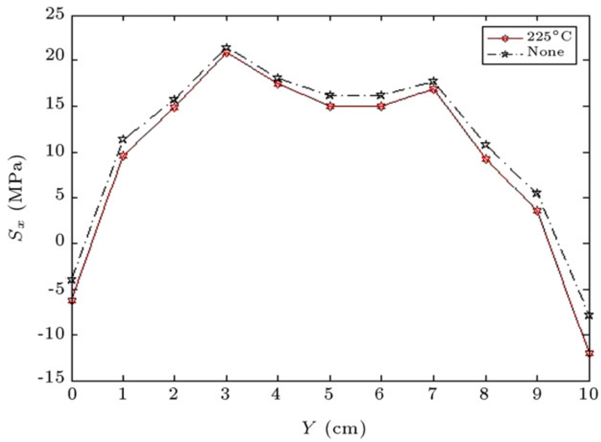


Figure 13: The effect of preheating treatment on residual stress distribution (Aluminum plate).

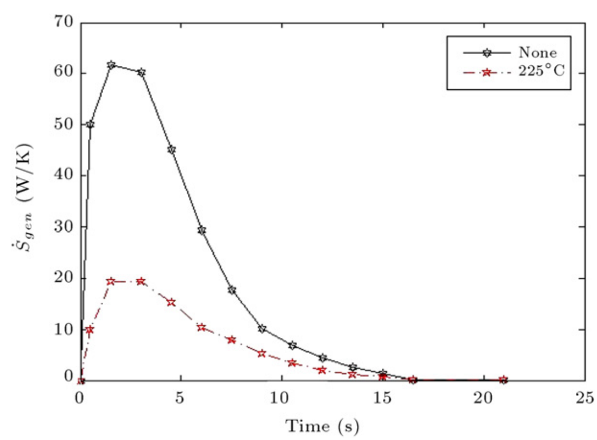


Figure 14: The effect of preheating treatment on entropy generation rate (Aluminum plate).

problem. Predicting the residual stresses of welding sequences accurately is extremely difficult. Hence, we try to estimate residual stress behavior, due to different welding sequences, through the proposed method, qualitatively.

Three adopted welding sequences are shown in Figure 15. Numerous welding sequences are used for welding in actual cases, but the three sequences (progressive, backstep and symmetric) presented in this paper have the greatest applications among different common welding sequences [10,12]. Thermal analysis of the welding sequence model is similar to the preheating one. Figures 16–18 illustrate temperature distributions for mentioned sequences. Based on temperature distributions, the entropy generation rate can be obtained. The procedure is similar to the preceding one for preheating treatment. In other words, first the entropy generation rate is plotted, with respect to time (Figure 19). Then the area under the curve (Figure 19) is calculated and the total entropy generation is calculated for each sequence, independently (see Table 2). The present results show that in the symmetric sequence, less entropy is generated than progressive and backstep sequences. On the other hand, as revealed in Figure 20, the residual stress values of symmetric welding are smaller than those of other welding sequences, similarly. Therefore, present residual stress behavior, due to these welding sequences, is comparable with that of entropy generation (Table 2). According to the results of the proposed method, one finds that symmetric welding caused minimal residual stress in comparison with other investigated sequences. This matter is achieved without obtaining residual stress magnitudes directly, which is very complex and time consuming.

It is worth mentioning that the above procedure is also applicable to other welding parameters, using both analytical and/or numerical models [26].

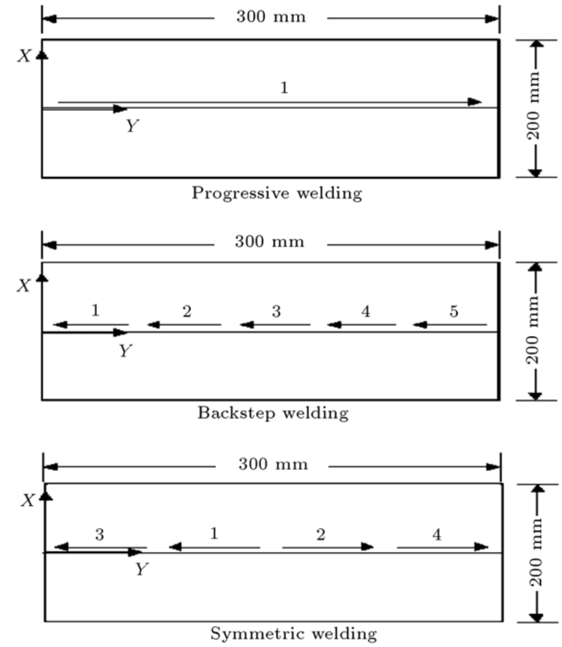


Figure 15: Three common welding sequences for thin wall butt-welds [10].

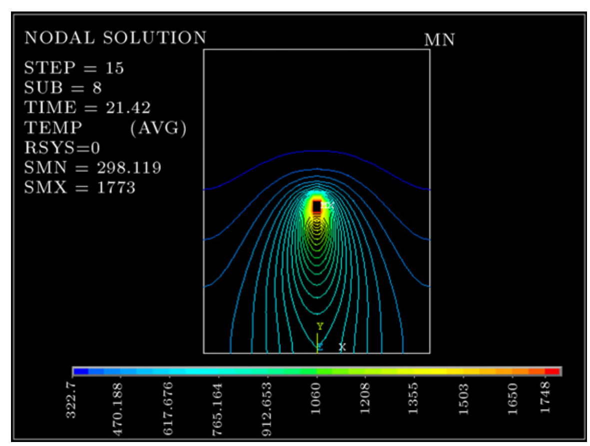


Figure 16: Temperature contours around the weld pool in progressive welding (when half of plate has been welded).

Table 2: Variation of total entropy generation with respect to three common welding sequences.

Sequences	Total entropy generation (J/K)
Progressive	74.2
Backstep	72.3
Symmetric	64.9

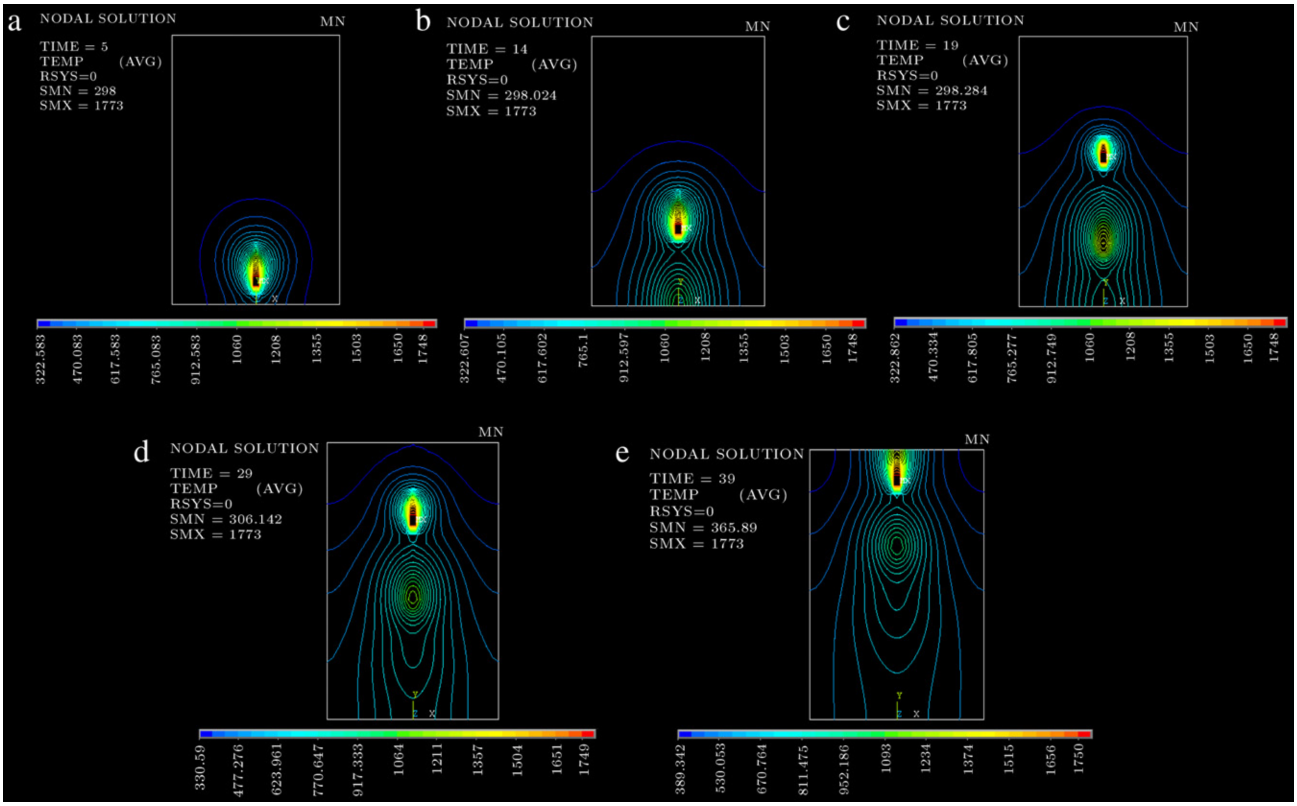


Figure 17: Temperature distribution in backstep welding. (a) First step; (b) second step; (c) third step; (d) fourth step, and (e) fifth step.

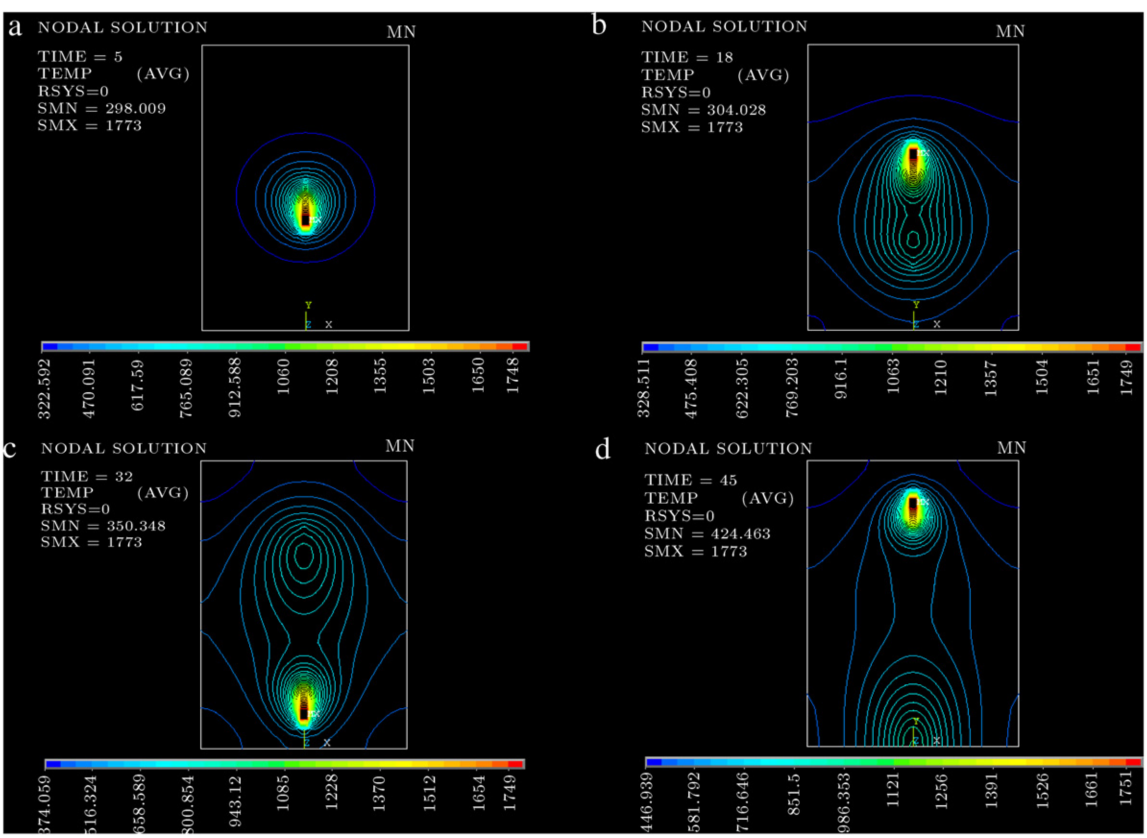


Figure 18: Temperature distribution in symmetric welding. (a) First step; (b) second step; (c) third step; and (d) fourth step.

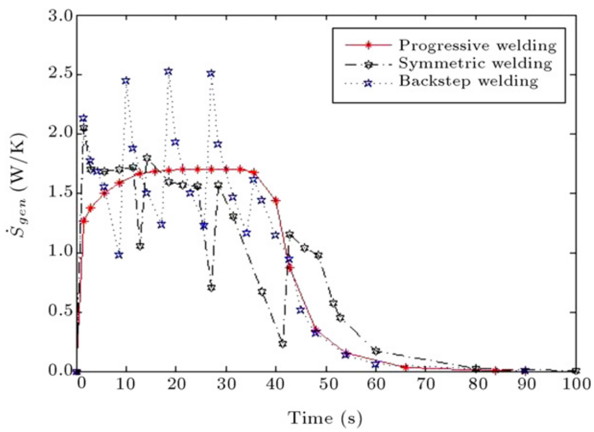


Figure 19: Entropy generation rate variation with time, due to different welding sequences.

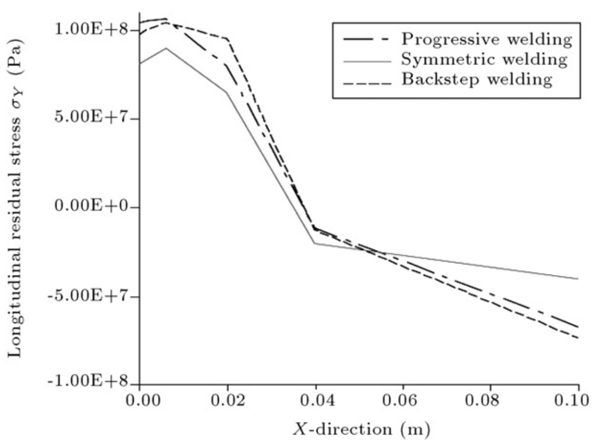


Figure 20: Longitudinal residual stress distribution along the X-direction for different welding sequences [10].

7. Conclusions

Based on the above discussion, one can conclude that:

1. The thermal field plays an important role in generation of entropy and residual stress during welding processes.
2. Preheating and selecting a proper welding sequence are both suitable approaches for reducing residual stresses.
3. The behaviors of entropy generation and residual stress distribution, with respect to different welding conditions, such as preheating and welding sequences, are very similar.
4. By studying entropy generation behavior, we found that the higher the preheating temperature, the lower the residual stresses would be.
5. We also realized that among three common welding sequences for single-pass welding, symmetric welding creates less residual stress and entropy generation in weldments.
6. The entropy generation rate can be used as a criterion for comparing the effects of various preheating temperatures and welding sequences on residual stresses.
7. The proposed method in this paper is suitable for predicting residual stress distribution in welded parts, qualitatively.

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